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RESEARCH ARTICLE

Organization of the upper limb movement for piano key-depression differs between expert pianists and novice players

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Abstract The present study investigated the expert-novice difference in the organization of upper-limb movement for the key-depression on the piano. Kinematic and electromyographic recordings were made while experts ($N = 7$) and novices ($N = 7$) of classical-piano players performed a right hand octave keystroke to produce four different sound dynamics. The joint torque generated at the key-bottom moment (key-force torque) was also estimated. At all sound dynamics, the experts showed a larger finger attack angle, more flexed shoulder, wrist, and MP joints, more extended elbow joint, and smaller key-force torque at the MP joint than the novices. The level of co-activation in the finger flexor–extensor muscles during the period prior to the key-bottom moment was also lower for the experts. To attain the large attack angle by the experts, as the fingertip depressed the key to the bottom, their shoulder was actively flexed, the forearm was thrust forward, and the hand was rotated forward. The novices, on the other hand, actively extended their shoulder to move the forearm and hand downward to depress the key. These results confirmed a substantial difference in the key-depression movement organization between the experts and novices. These findings also suggest that experts use a synergistically organized multi-joint limb motion that allows them to minimize the biomechanical load and muscular effort to the distal muscles. The novices, on the other hand, tend to rely on a rudimentary synergy of joint motion developed through daily experience.

Keywords Motor control · Motor learning · Movement planning · Inter-segmental dynamics · Stiffness control · Synergy · Pianist

Introduction

Keystrokes on the piano commonly start with lifting the whole arm to some height, dropping it for the finger(s) to hit and depress the target key(s), and lifting the hand again to release the key depression. A comparative study of keystrokes by expert and novice pianists can provide an opportunity to understand the effect of long-term training on the control and organization of a complex multi-joint motor action. A recent study of piano keystrokes by the present authors clearly demonstrated that the spatio-temporal organization of the downward swing motion of the whole upper limb differed between the experts and novices (Furuya and Kinoshita 2007). The experts commonly organized the motion in a proximal-to-distal sequence, where the timing of movement onset for the moving joints was arranged in the order from the proximal to distal over a wide range of sound dynamics. The novices, on the other hand, did not show such an organization at any level of sound dynamics. The experts also had a longer and greater deceleration of movements at the shoulder and elbow joints than the novices during the period when angular velocity at their adjacent distal joints was increasing. This finding suggested that greater passive (interaction) torques were developed at the elbow and wrist for striking the keys for the experts than the novices. Using an early kinematic recording method of “kymocyclography”, Bernstein and

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Popova in 1930 investigated the kinematics and kinetics while professional pianists were performing repetitive octave keystrokes at varied striking tempi and loudness levels (see, Kay et al. 2003). They found that prior to the finger-key contact moment, there was a brief braking period of the arm downswing by active muscular torque directed upwards at the elbow and wrist joints. This also suggested the effective exploitation of interaction torques as the expert pianists swing their arm to hit the keys. Although these studies provided some evidence about the organization of the downswing motion, so far very little attention has been paid to the effect of passive forces from the end of downswing through the key depression.

Studies of ball throwing performed by the skilled and unskilled arms suggested that an interaction torque at the wrist joint produced due to forearm translational deceleration before the moment of ball release helped in the increased wrist flexion velocity only for the skilled arms (Gray et al. 2006). It is possible to hypothesize that the trained pianists have learned the most efficient way to move their upper limb for key depression. This could involve in large forearm translational deceleration before the key depression phase starts so that an associated interaction torque can be effectively exploited for the flexion of their wrist and metacarpophalangeal (MP) joints during key depression. For the novice players, on the other hand, such movement organization could be less clear. In addition, the muscular activity to facilitate these distal joint motions would also be larger for the novices than the experts. The primary purpose of the present study was therefore to test the above hypothesis using expert and novice piano players. To this end, we used a simple right arm octave keystroke performed from some height above the key as a motor task in this study.

Another problem that needs to be investigated is the use of an appropriate posture of the hand and fingers at the end of key depression, the so-called “attack angle”. This has also been argued with an efficient behavior of key depression, posing less mechanical stress to the finger joints (Harding et al. 1993; Jindrich et al. 2004). When depressing the keys, the reaction force at the fingertip can be around 8 N with weak sound dynamics, but it reaches as high as 50 N with strong sound dynamics (Askenfelt and Jannson 1991). Repetitive keystrokes can cumulatively damage muscles, tendons, and joints of the hand and forearm over the time (Dennerlein 2005), thus leading to so-called “playing-related musculoskeletal disorders (PRMDs)” (Altenmuller 2003; Bragge et al. 2006; Furuya et al. 2006b). One suggested technique to reduce the physical load when the fingers are experiencing the maximum key reaction force is for the pianists to assume their hand posture with the fingers at an appropriate angle relative to the key (Harding et al. 1993; Sandor 1995). Using a biomechanical finger model, Harding et al. (1993) earlier provided evidence that the MP joint torque generated by the key-force and normal force at the distal interphalangeal (DIP), proximal interphalangeal (PIP) and MP joints could be minimized when depressing the piano key with a large MP flexion angle and a large orientation angle of the finger segment relative to the key. This was attributed to the fact that within the range from 0° to 90° at the attack angle, its increase causes finger joint centers to be closer to the key reaction force vector, thus resulting in decreases in the finger joint torques. By actually measuring the angles at the finger joints when subjects pressed a computer key, Jindrich et al. (2004) found that increase in flexion at the MP joint by 7° could cause a 32% reduction of the joint torque, thus requiring 45% less stiffness of the joint to oppose the key reaction force. Although researchers recommend the use of a larger attack angle for the reduction of keystroke-related joint torque at the finger, neither the actual hand and arm postures nor the related torques at the joints of the upper extremity in the pianists of different skill levels during keystrokes has been reported.

A secondary purpose of the present study was therefore to investigate the expert-novice difference in the posture of the hand and arm, and associated joint torques at the moment of maximum key depression (the key “bottom”). The findings from the modeling studies allowed us to hypothesize that for eliciting the same target sound the trained pianists would use a larger attack angle, and thereby reducing the associated key-force torque and muscular effort for key depression in comparison to the novices.

Methods

Participants

Eight active expert pianists (3 males and 5 females, mean age ± SD = 24.0 ± 3.0 years) with more than 15 years of classical piano training, and eight novice piano players (3 males and 5 females, age = 20.6 ± 4.4 years) with less than a year of piano training served as participants in the present study. All of the expert pianists had received a prize(s) at domestic and/or international classic piano competitions. All participants were right-handed, as determined by the Edinburgh MRC Handedness Inventory (Oldfield 1971). Informed consent was obtained from all participants, and the study was approved by the ethics committee at Osaka University.

Experimental apparatus and key-striking task

The experimental apparatus used were a Yamaha U1 upright piano, an 8-channel telemetric electromyography

(EMG) recording system (Nihon Koden Co. WEB-5000), two 2-D position sensor systems (C5949, Hamamatsu Photonics Co. Japan), a sound-level meter (NA-27, Rion Co. Japan), and a stereo sound amplifier. The sound-level meter was placed 1 m above the keyboard and collected sound signals at a sampling frequency of 900 Hz. The experimental task was a right-hand octave keystroke, a simultaneous strike of the 35th (G3) key by the thumb and the 47th (G4) key by the little finger. The keys were 166 mm apart. This movement task was chosen to induce a whole arm movement, as well as to minimize the medio-lateral and pronation–supination movements of the hand and arm during the keystroke to permit a 2-D kinematic analysis. In a 3-D kinematic analysis of the same movement performed by three experts and three novices, we earlier measured the extent of these non-sagittal plane movements (Furuya et al. 2006a). At the *f* level of sound dynamics, the movement range and peak velocity of a marker on the ulnar styloid process in the medio-lateral direction in these participants did not exceed 9 mm and 89 mm/s, respectively, which were around 10% of the corresponding values in the vertical direction. The range and peak velocity of pronation of the forearm were less than 0.07 rad and 0.37 rad/s, respectively, which were also consider to be fairly small. Because these results indicate that the non-sagittal plane movements in the present motor task were quite small, within the limitation of the present kinematic technique, the measurement error introduced is judged to be small enough to warrant the validity of the present results of the joint kinematics. In the experiment, the participant started with lightly touching the fingertips of the right hand on the keys, lifted his/her right arm/hand to a self-determined height at a self-determined speed, stroked the keys in a short tone production (a staccato touch) at a designated level of tone, lifted the hand and arm again as a follow-through to a self-determined height, and returned to the initial position. The left arm and hand were kept relaxed and placed on the side of the trunk while the trunk was in an upright position with minimum movement.

Based on our previous study, four target sound pressure levels (SPLs) of 103, 106.5, 110, and 113.5 dB were chosen in this study, which roughly corresponded to loudness for a piano (*p*), mezzo-piano (*mp*), mezzo-forte (*mf*), and forte (*f*), respectively (Furuya et al. 2006a). For each participant, kinematic, EMG, and simultaneous sound data were collected from thirty successful strokes at each of the target SPLs with an approximately 10-s trial-to-trial interval. The target SPL was a pre-recorded piano sound on a minidisk, which was presented from a set of speakers placed on the top of the piano. With the help of the experimenter providing feedback regarding the difference in the produced and given SPLs, each participant practiced the task until he/she could reduce the errors to within above or below 0.9 dB of the target SPL before the data collection.

Data-acquisition procedures

Movement of the right upper limb in the sagittal plane was recorded using one of the position sensor cameras (sampling freq. = 150 Hz) located at 3.5 m on the right side of the participant. The LEDs for this were mounted on the skin over the tip of the little finger and the centers of the metacarpo-phalangeal (hand), styloid process (wrist), head of radius (elbow), and coracoid process (shoulder) joints (Fig. 1). To minimize the problem of the measurement errors, a rotational center of each joint was carefully estimated. For this, we always video recorded joint movement after attaching the LEDs on the skin to visually check if

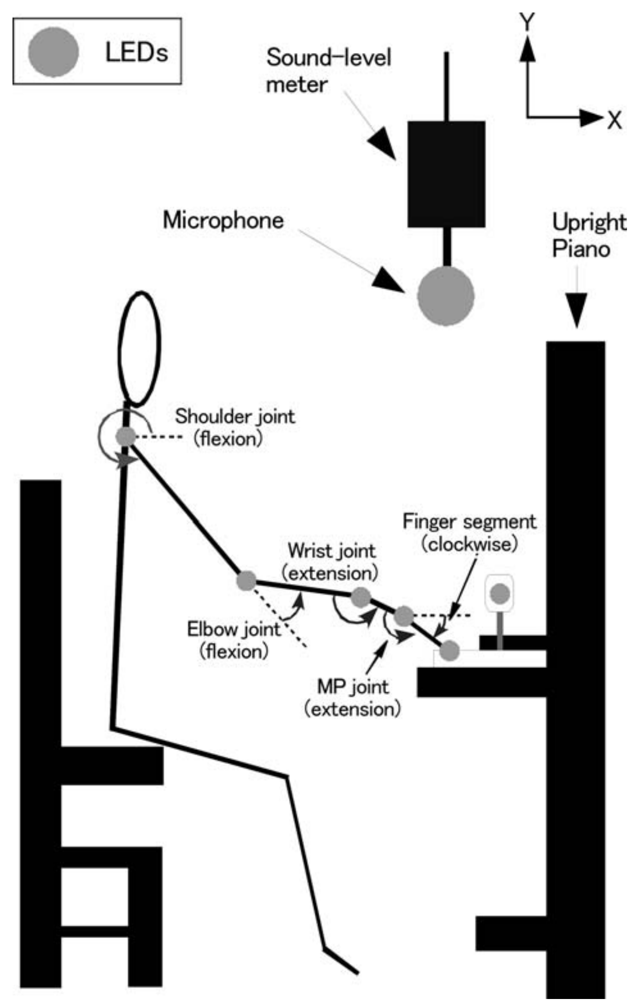

Fig. 1 LED placement and definition of joint angles. The counter-clockwise direction is defined as a positive direction in angular displacement at each joint. Positive angular displacement describes flexion movement at the shoulder and elbow joints and extension movement at the wrist and MP joints

each LED is positioned at the center of rotation of the target joint. The data were digitally smoothed at the cut-off frequency of 10 Hz using a second-order Butterworth digital filter. Angular displacement at the MP, wrist, elbow and shoulder joints, and that of the little finger relative to the key surface were then numerically calculated using an inner product method. Because there was no position data at the PIP and DIP joint centers in the present experiment, we approximated the MP joint angle as the angle formed by the vectors from the MP joint center to the fingertip of the little finger and from the MP joint center to the wrist joint center. The attack angle was then defined by the angle of the vector from the MP joint center to the fingertip of the little finger relative to the horizontal axis. The definition of these joint angles is shown in Fig. 1.

The G3-key kinematics was recorded using another position sensor camera located 0.65 m left of the key, and an LED placed on the key surface. The onset of the key descending movement ("the finger-key contact moment") was determined when the calculated vertical velocity of the key exceeded 5% of its peak velocity. The movement of the G4 key was not measured due to difficulty in placing a close-up view camera on the right side of the piano without interfering with the kinematic recording of the hand movement by the other far view camera. In a pre-test of octave keystrokes performed at various loudness levels, a significant spatio-temporal synchrony of the G3 and G4 keys had been confirmed ($r > 0.76$).

Using the EMG system, the electric activities were recorded from the right side of the six selected limb muscles associated with flexion/extension movement of the shoulder, elbow, wrist and finger. The selected muscles were the posterior and anterior deltoids (PD and AD, respectively), triceps brachii lateral head, biceps brachii, flexor digitrum superficialis (FDS) and extensor digitrum cummunis (EDC) muscles. Pairs of Ag/AgCl surface disposal electrodes were placed at the estimated motor point of each target muscle with a 20-mm center-to-center difference. Electrode placement was always carefully chosen to minimize any cross talk from adjacent muscles. At each electrode position, the skin was shaved, abraded, and cleaned using isopropyl alcohol to reduce the source impedance. The EMG signals were amplified (5,000×) and sampled at 900 Hz using the A/D converter interfaced with a personal computer. They were then digitally high-pass filtered with a cut-off frequency of 20 Hz and root-mean squared. In order to normalize these EMG data for each muscle for each participant, maximum voluntary contraction (MVC) EMG data was obtained for each muscle by asking the participant to perform maximum flexion or extension isometric force production against a stationary object for a 5 s period. Each subject was verbally encouraged to achieve maximal force at a designated joint angle. During a MVC trial for the FDS and EDC muscles, the wrist joint was kept at 180° (the neutral position), and for the biceps and triceps muscles, the elbow joint was kept at 90°. For the PD and AD muscles, the shoulder was kept zero degrees (the neutral position). A percent MVC value was then calculated using the mean value of the middle 3-s period MVC data.

Data analysis

For the graphic representation of the kinematic, kinetic and EMG data, mean curves of 30 keystroke trials at each loudness level for each subject were generated by a point-by-point averaging process based on a predetermined common point for each trial. The common point used was the moment of the key lowest position, which was set as a time zero point in the present study. For the statistical analysis of the data, kinematic, kinetic, and EMG variables were also computed from the data at each keystroke trial. Kinematic variables were (1) the angle of the finger segment relative to the key (= attack angle), and the angles for the MP, wrist, elbow and shoulder joints at the moment of key-lowest position, (2) movement amplitudes of the rotation of the finger segment, and the rotations of the MP, wrist, elbow and shoulder joints during the key-depression period (between the moment of finger-key contact and the moment of the key lowest position). Because the staccato touch in our motor task required lifting the fingertips as quickly as possible when it reached the key's lowest position, there was nearly no dwelling time after key-depression. However, in some cases, we observed the period in which the key position data was kept nearly constant at around the bottom of the range of the key's movement. In this case, the key's lowest moment was determined by the time when the key initially reached its lowest position. The moment of key lowest position was evaluated because the magnitude of key reaction force reaches its maximum value at around this moment (Askenfelt and Jannson 1991; Harding et al. 1989). Kinetic variables were joint torques generated by the key reaction force when assuming that a given magnitude of reaction force was applied to the fingertip at the moment of key-lowest position. Complete equations of motion used for kinetic computation are listed and explained in detail in the Appendix.

The EMG data were also quantified to evaluate the co-activation of the agonist and antagonist muscles, using the method described in previous studies (Kellis et al. 2003). Briefly, for each participant, the EMG data were normalized in a MVC value, and then full-wave rectified and low pass filtered at 6 Hz, yielding the linear envelopes of each muscle EMG. After subtracting the mean EMG value during the rest period from this normalized and rectified EMG data for each muscle, the coactivation index was calculated for each trial by finding the overlap between the agonist and antagonist curves during the time window from 200-ms before the moment of finger-key contact to the moment of key lowest position. The coactivation index value was then divided by the duration of this time window to obtain the averaged value. Namely, the following equation was used to compute the coactivation index value for the forearm, upper-arm, and shoulder muscles.

$$\text{coactivation index} = \left(\int_{t1}^{t2} \mathrm{EMG_{agon}}\,dt + \int_{t2}^{t3} \mathrm{EMG_{ant}}(t)\,dt \right) / \Delta T$$

where $t1$ and $t2$ denote the period where the agonist EMG activity is less than the antagonist EMG, whereas $t2$ and $t3$ denotes the period where the antagonist EMG activity is less than the agonist EMG; $t1$, $t2$, and $t3$ are within the period from 200-ms before the moment of finger-key contact to the moment of key lowest position; ΔT is the duration from 200-ms before the moment of finger-key contact to the moment of key lowest position.

Statistical analysis

The means for each of the kinematic, kinetic, and EMG variables were computed from the 30 trials at each of the four loudness levels for each participant. Statistical analyses were then carried out on these mean values using R statistical software (Ver. 2.5.1). A two-way multivariate ANOVA (MANOVA) with repeated measures was first used to examine the effect of group (2 levels: the expert and novice groups) and loudness (4 levels: *p*, *mp*, *mf*, and *f*), as well as their interaction on a set of kinematic, kinetic, and EMG variables. The P value of 0.05 was used for the evaluation of Wilks' lambda value. Multiple two-way ANOVAs with repeated measures were further performed to evaluate their effects on each of the dependent variables examined. The P value of 0.01 was used for the evaluation of the ANOVA results in order to reduce the risk of making Type I errors. A post hoc analysis was performed by using the Tukey test ($P < 0.05$).

Results

Joint kinematics for keystroke

Representative mean time–history curves of the joint and attack angles, and key's vertical displacement at the *f* and *p* dynamics by one of the experts and one of the novices are shown in Fig. 2. During the descending phase the shoulder and MP joints for the experts were more flexed while their elbow joint was less flexed compared with the novices. For the experts, shoulder flexion started to occur slightly before the moment of finger-key contact. For the novices, on the other hand, the shoulder joint continued to extend before and after the finger-key contact moment. These were also common at the *mp* and *mf* dynamics. During the period of key depression (the period indicated by an arrow in Fig. 2), the shoulder, wrist, and MP joints for the experts underwent simultaneous flexion movement while their elbow joint was extended. The novices, on the other hand, used predominately the wrist flexion and elbow extension for depressing the keys.

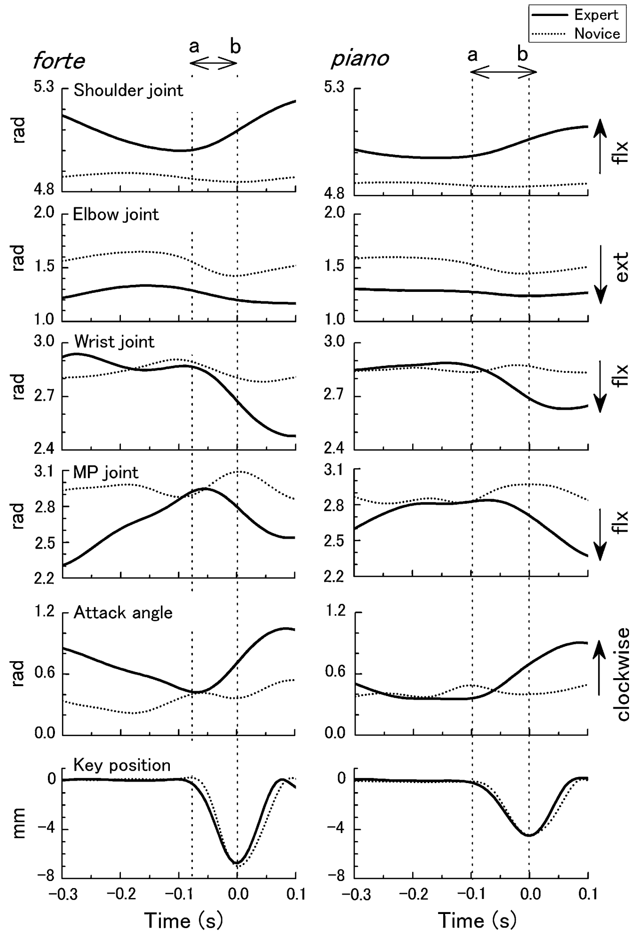

Fig. 2 The time-history curves of the key vertical position, the angular position of the finger-segment relative to the horizontal axis, and the relative joint angle for the shoulder, elbow, wrist and MP at *f* and *p* loudness levels in one representative expert (*solid line*) and novice (*dotted line*) pianist. The *curves* represent the average of 30 keystrokes. The *dotted vertical lines* indicate the moment of finger-key contact (**a**), and the moment of the lowest key position, when the key-depression was ended (**b**). The *arrow* indicates the key-depression phase

The segmental movements of these examples from the finger-key contact moment to the maximum key depression

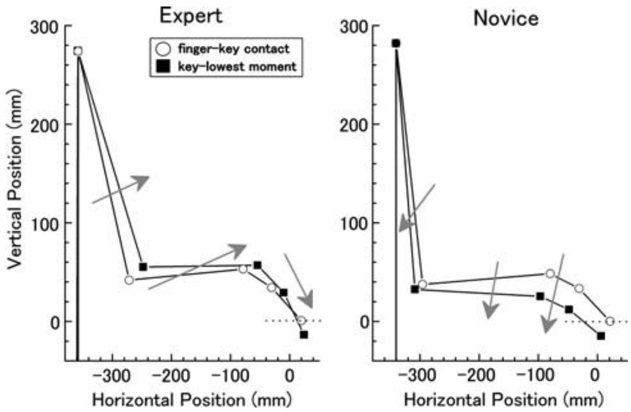

Fig. 3 Stick figures of the upper limb at the finger-key contact moment (*circle symbol*) and the key-bottom moment (*square symbol*) when striking at *f* sound dynamics for one representative expert (*left panel*) and novice (*right panel*) player. A *dotted horizontal line* indicates the position of the key-surface

moment are illustrated using their stick pictures in Fig. 3. The experts moved the upper arm and forearm upward and forward. They simultaneously moved their hand forward and downward causing rotation of the hand at the fingertip as a pivoting point. Therefore, a clear wrist and MP joint flexion was observed with key depression. In contrast, the novices moved their upper arm downward and backward, and the forearm and hand/finger downward without any distinct wrist and MP joint flexion.

The group means for the amplitude of the flexion and extension movements at the shoulder, elbow, wrist, and MP joints during the key depression phase are shown in Fig. 4a–f. At all SPLs, the experts had larger amplitude of flexion movement at the shoulder, wrist, and MP joints. The novices, on the other hand, had larger amplitude of shoulder and MP extension. To determine whether the group effect was statistically significant across all these movement amplitude values, MANOVA was first performed. Significant main effects of group (Wilks' lambda = 0.215, $P < 0.001$) and loudness (Wilks' lambda = 0.406, $P < 0.001$) was revealed, but their interaction was insignificant (Wilks' lambda = 0.857, $P = 0.973$). Two-way repeated measures ANOVA then confirmed that group differences were significant for shoulder extension ($F(1, 14) = 35.81$, $P < 0.001$), shoulder flexion ($F(1, 14) = 9.13$, $P = 0.009$), MP flexion ($F(1, 14) = 10.10$, $P = 0.006$), and MP extension ($F(1, 14) = 9.33$, $P = 0.009$), but not for the elbow extension and wrist flexion. For the amplitude of the MP joint flexion, the group × SPL interaction effect was also significant ($F(3, 42) = 5.09$, $P = 0.004$). The interaction effect indicated that with the generation of louder sound, the experts used larger flexion movement at the wrist and less flexion movement at the MP joint. The novices, on the other hand, maintained nearly a constant MP joint angle across all

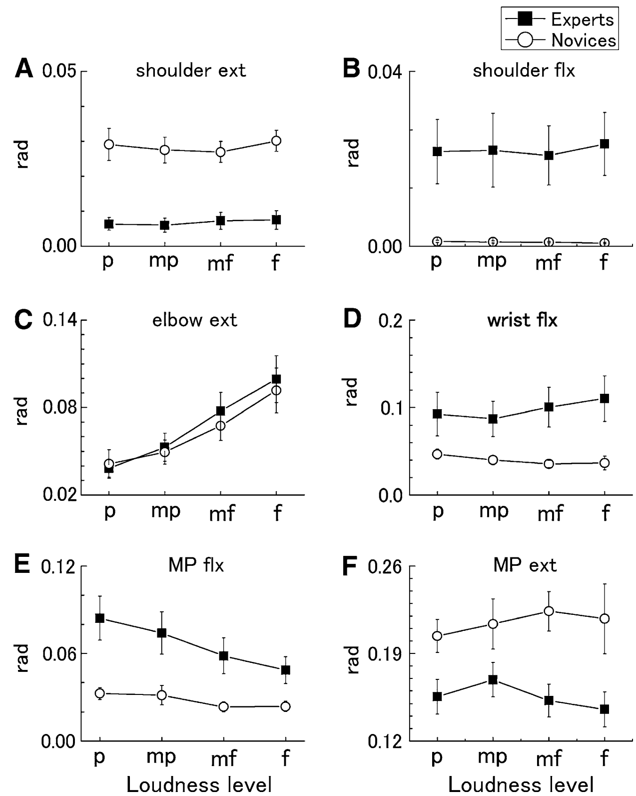

Fig. 4 The group means of the amplitude of joint rotation for shoulder extension (**a**), shoulder flexion (**b**), elbow extension (**c**), wrist flexion (**d**), MP flexion (**e**), and MP extension (**f**) during the key-depression phase at four loudness levels (*p*, *mp*, *mf*, and *f* indicate *piano, mezzo-piano, mezzo-forte*, and *forte*, respectively). *Error bars* represent ± 1 SE

SPLs. The elbow extension and MP flexion amplitude also had a significant SPL effect ($F(3, 42) = 57.43$, $P < 0.001$ and $F(3, 42) = 16.71$, $P < 0.001$, respectively).

Figure 5a–d show the group means of the joint angle at the maximum key depression moment at each SPL. Using the joint angle values at the MP, wrist, elbow and shoulder joints as dependent variables, MANOVA was performed. There was a significant main effect of group (Wilks' lambda = 0.298, $P < 0.001$). ANOVA was then performed for each of the joint angle, which revealed that the experts had significantly larger flexion at the shoulder ($F(1, 14) = 28.03$, $P < 0.001$), wrist ($F(1, 14) = 9.16$, $P = 0.009$), and MP ($F(1, 14) = 9.54$, $P = 0.009$) joints, and larger extension at the elbow joint ($F(1, 14) = 22.64$, $P < 0.001$) in comparison to the novices.

Attack angle

The attack angle increased sharply from the key-contact moment to the key bottom moment for the experts, while it was kept at a similar angle for the novices (see examples in

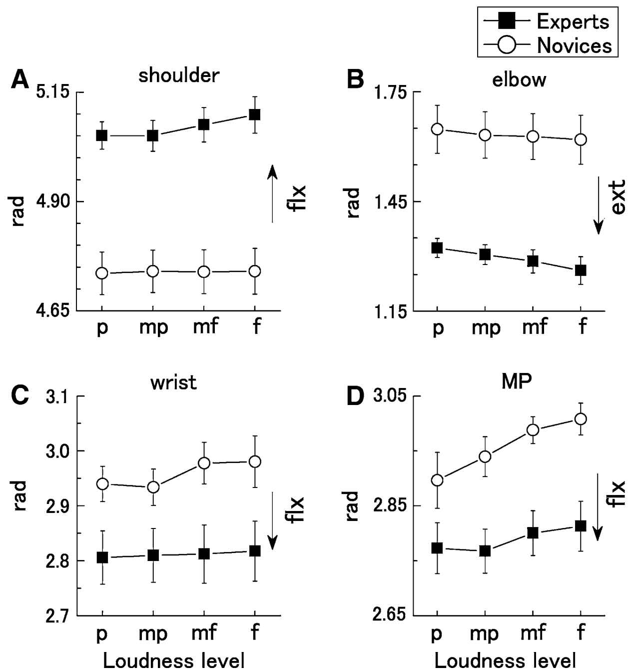

Fig. 5 The group means of the angles for the shoulder (**a**), elbow (**b**), wrist (**c**), and MP (**d**) joints at the key-bottom moment. *Error bars* represent ± 1 SE

Fig. 2). At all SPLs, therefore, the mean attack angles at the moment of the key bottom for all participants were significantly larger for the experts than the novices ($F(1, 14) = 25.58$, $P = 0.002$, Fig. 6a). The ranges of their angular rotation during the key depression phase were also significantly larger for the experts than the novices ($F(1, 14) = 9.17$, $P = 0.009$, Fig. 6b).

To examine how the experts achieved such a large increase in attack angle, a multiple-regression analysis was performed using the movement amplitude of their MP flexion and extension, wrist flexion, elbow extension, shoulder extension and flexion as independent variables. The R^2 value of 0.83 was obtained in this analysis. The highest contribution to this was the shoulder flexion (semi-partial correlation = 0.36), which was followed by the finger flexion (0.24), and wrist flexion (0.20). The contribution by the others was all less than 0.11.

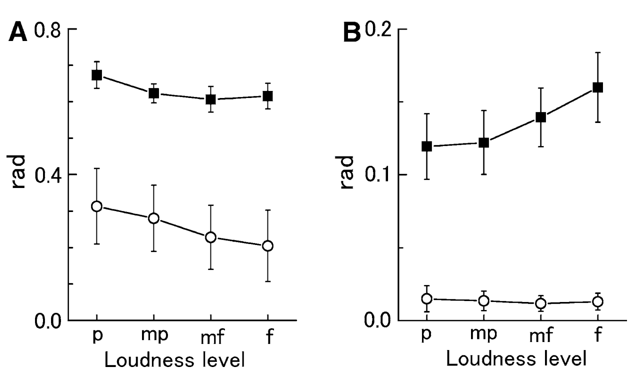

Fig. 6 The group means of the attack angle at the key-bottom moment (**a**), and the range of its angular rotation during the key-depression phase (**b**). Error bars represent ± 1 SE

Deceleration of translational vertical movement of the upper limb segments

Translational and/or rotational deceleration of the proximal segment can serve as an estimate of interaction torque occurring at the adjacent distal segments during multi-segment motion (Debicki et al. 2004; Gray et al. 2006; Hore et al. 2005a). Figure 7 shows the mean values of maximum translational deceleration of the upper and forearm, and the hand for each group during the period before the moment of key-bottom (Fig. 7). MANOVA performed using the data of all segmental decelerations revealed the significant main effects of the group (Wilks' lambda = 0.427, $P < 0.001$). ANOVA for each segment further revealed that the upper arm had significant effects

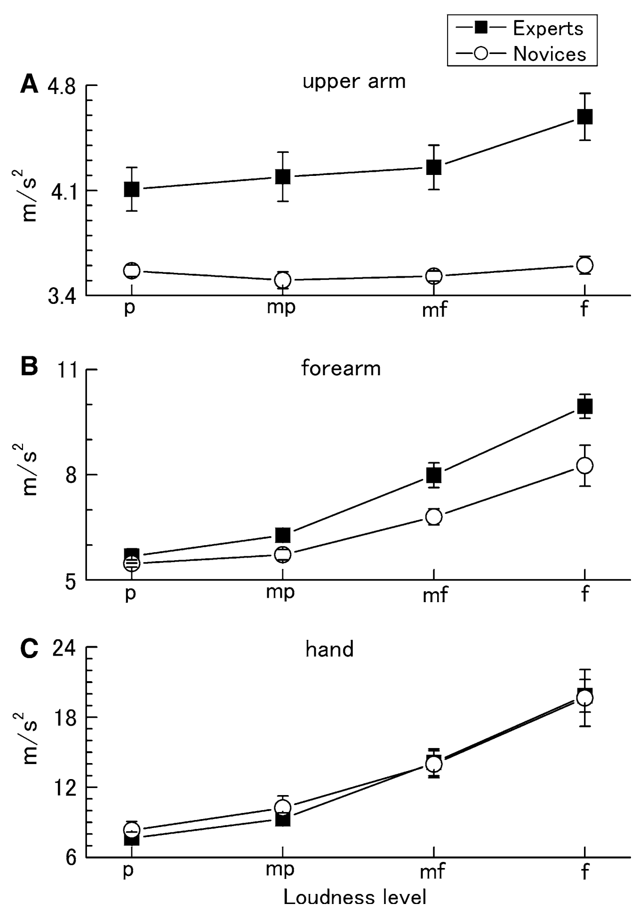

Fig. 7 The group means of the maximum deceleration of translational descending movement at the upper-arm (**a**), forearm (**b**), and hand (**c**) segments during the period from the initiation of hand descent to the key-lowest moment at all loudness levels. Error bars represent ± 1 SE

of group × loudness interaction ($F(3, 42) = 5.61$, $P = 0.003$) and group ($F(1, 14) = 25.58$, $P < 0.001$), and the forearm had a group effect ($F(1, 14) = 11.52$, $P = 0.004$). The results indicated that a larger descending deceleration occurred at both the upperarm and forearm segments during keystroke for the experts than the novices, and this difference was larger at louder sound generation for the upper-arm. These results suggest that the interaction torques produced at the elbow and wrist joints associated with the braking action at the shoulder joint are larger for the experts than the novices. These results also imply no difference in interaction torque at the MP joint to propel the finger to depress the keys.

Joint torques at the moment of key bottom

Figure 8 shows the group means of estimated key-force torques that are generated around the MP, wrist, and elbow joints at the key-bottom moment. The complete equations of motion used are listed in the Appendix. MANOVA performed using the data of all three joint torques revealed significant main effects of group (Wilks' lambda = 0.281, $P < 0.001$) and loudness (Wilks' lambda = 0.014, $P < 0.001$), and the effect of group × loudness interaction (Wilks' lambda = 0.590, $P < 0.001$). ANOVA further revealed that group × loudness interaction ($F(3, 42) = 27.61$, $P < 0.001$) and group ($F(1, 14) = 30.30$, $P < 0.001$) effects were significant only at the MP joint. The main effect of SPL was significant at all joints. The interaction effect indicated that the group difference in the MP joint torque was greater for the louder sound production. No group × SPL interaction was found at both the wrist and elbow joints. For the group effect at the MP joint, post hoc comparisons using a Tukey test revealed a significant group difference at each SPL (Fig. 8a). The mean values of the novices were above 1.4 times of those for the experts at all SPLs.

Muscular activity

A typical example of the muscular activities of the forearm (EDC and FDS), upper arm (Biceps and Triceps), and shoulder (AD and PD) muscles by one expert and novice at the *f* and *p* levels is shown in Fig. 9. About 50–100 ms before the moment of finger-key contact, the expert increases the activity at the shoulder and elbow flexor muscles (AD and Biceps), whereas the novice shows a burst of the muscular activity at the shoulder and elbow extensors (PD and Triceps) at both SPLs. Slightly before the finger-key collision, the antagonists of these muscles increases their activities, thereby showing muscular coactivation at the shoulder and elbow muscles. For the experts the onset of the AD muscular activity in relation to the finger-key contact moment was commonly about 50 and 100 ms before when striking the keys at the *f* and *p* levels, respectively. For the novices, on the other hand, these values were about 50 ms later than those for the experts. For the forearm muscles, in contrast, there was a simultaneous increase of both EDC and FDS activity about 100–150 ms before the moment of the finger-key contact. The coactivation of the forearm, upper arm and shoulder muscles continued during the key depression phase. The onset and magnitude of these muscular activities were commonly earlier and larger for the novice than those for the expert, respectively. The magnitude of the activities was also clearly larger at a louder sound for both groups of players.

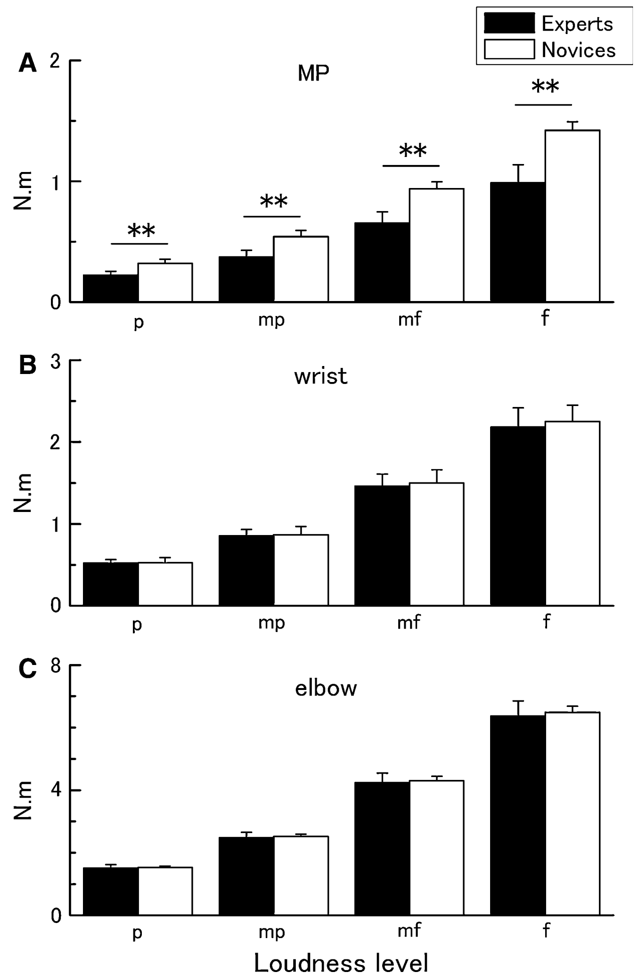

Fig. 8 The group means of the estimated key-force torque at the MP (**a**), wrist (**b**) and elbow (**c**) joints at the key-bottom moment. See the detailed explanation in the "Appendix"

The mean value of the coactivation index for each group increased with the SPL at all three portions (Fig. 10). MANOVA for the three coactivation index values at the three body portions revealed significant main effects of group (Wilks' lambda = 0.645, $P < 0.001$) and loudness (Wilks' lambda = 0.544, $P < 0.001$). Their interaction

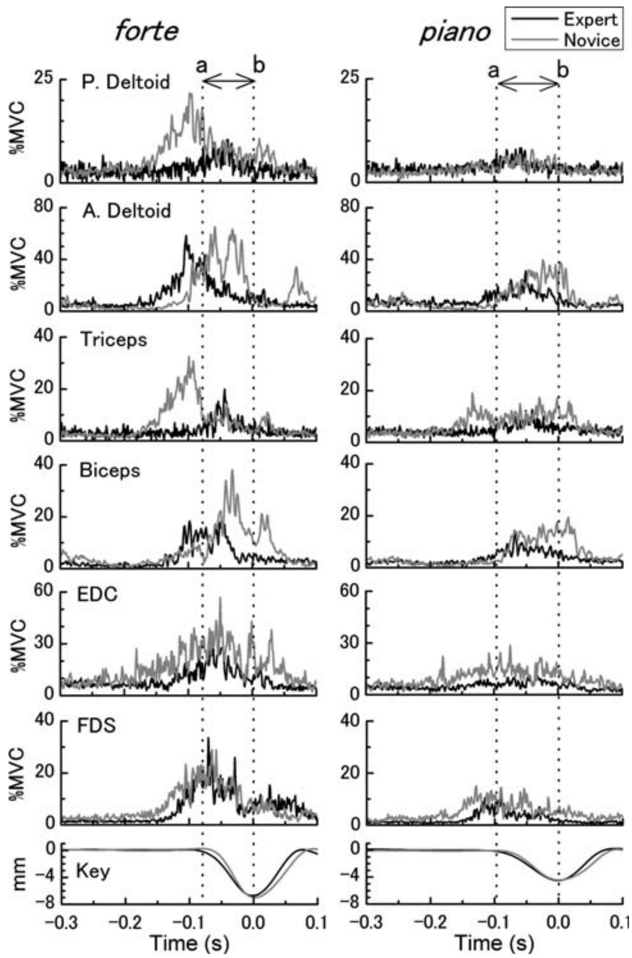

Fig. 9 Time history curves of the root mean squared and normalized EMGs for the posterior deltoid, anterior deltoid, triceps brachii, biceps brachii, extensor digitrum cummunis (EDC) and flexor digitrum superficialis (FDS) muscles at *f* and *p* loudness levels in one representative expert (black line) and novice (gray line) pianists. The data presented are from 30 striking trials. The dotted vertical lines indicate the moment of finger-key contact (**a**), and the moment of the lowest key position, when the key-depression was ended (**b**). The arrow indicates the key-depression phase

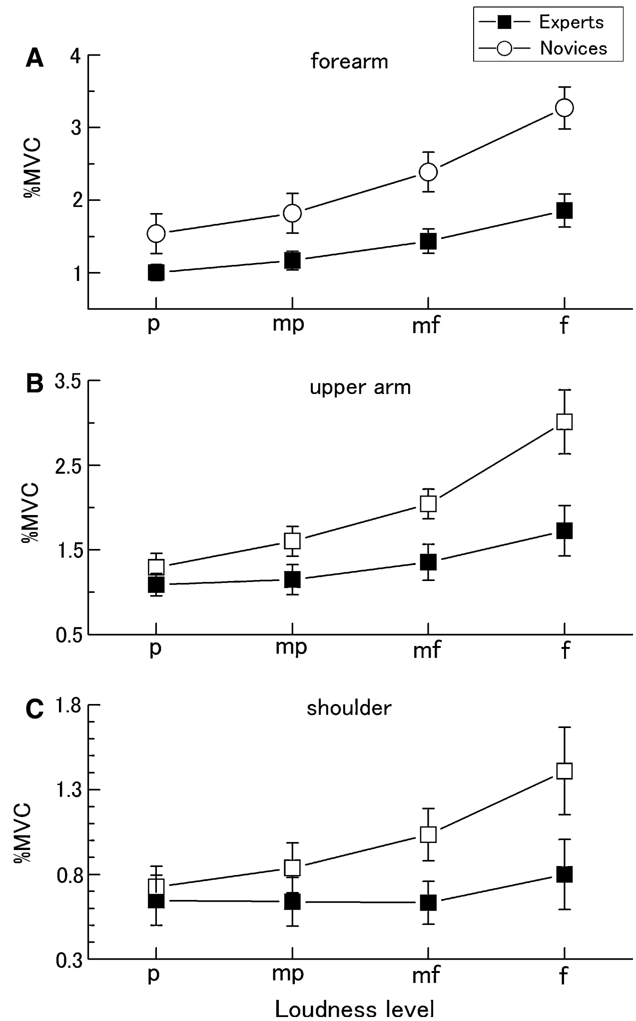

Fig. 10 The group means of the coactivation index for the agonist-antagonist pairs of forearm (**a**), upper arm (**b**), and shoulder (**c**) muscles. *Error bars* represent ± 1 SE

effect was insignificant (Wilks' lambda = 0.889, $P = 0.683$). ANOVA further revealed that main effect of SPL was significant for all muscles (the forearm: $F(3, 42) = 78.31$, $P < 0.001$; the upper arm: $F(3, 42) = 28.77$, $P < 0.001$; the shoulder: $F(3, 42) = 13.71$, $P < 0.001$), whereas the group effect was significant only for the forearm muscles ($F(1, 14) = 9.12$; $P = 0.009$).

Discussion

The expert-novice difference in deceleration of the limb before finger-key contact

In line with our hypothesis, the experts had a greater amount of translational deceleration of the upper arm prior to the finger-key contact moment than the novices, thus showing an expert-novice difference in preparatory motion of the proximal segment for key depression. It is now known that in skilled multi-joint limb movements, deceleration at the proximal limb generates interaction torques at the adjacent distal joint (Bagesteiro and Sainburg 2002; Gray et al. 2006; Hirashima et al. 2007; Hore et al. 2005a). A greater magnitude of deceleration in the upper and forearm prior to the finger-key contact moment in the experts thus must have produced greater interaction torques at the elbow and wrist joints than in the novices. As for the MP joint, however, the translational deceleration of the hand did not differ between the experts and novices, suggesting that the resulting interaction torque at their MP joints would be similar. The reduced activity at the forearm muscles could therefore be principally attributed to a better exploitation of the interaction torques at the wrist joint.

Bernstein and Popova in 1930 studied the kinematics and kinetics of arm motion while the expert pianists performed repetitive octave keystrokes at varied loudness levels and striking tempi (Kay et al. 2003). Their data showed that at slower striking tempi, torques at the elbow and wrist joints increased in synchrony with an increase in SPL while a torque at the shoulder joint remained nearly constant at all SPLs. They concluded that the elbow and wrist represent a tightly linked system for loudness control, and their biomechanical unity is independent of the shoulder. This is apparently different from our findings of the experts who had a greater amount of braking motion at the shoulder joint motion to propel the forearm and hand by the generated interaction torques at the elbow and wrist joints. These differences could be partly due to that the muscle torques defined in Bernstein and Popova's study contained not only the contribution by active muscular force but also those by the interaction and key-force torques. A more precise kinetic analysis that computes the muscular torque by subtracting the interaction, gravitational, and key-force torques from the net joint torque is thus called for in the future study.

One may question why the novices did or could not decelerate their upper arm to facilitate elbow extension and wrist flexion by the use of generated interaction torques. In a simulation of a ball throw task, Hirashima et al. (2003) demonstrated that a small change in the onset time of proximal limb deceleration would modulate not only the timing of resulting interaction torque at the distal joint(s) but also its magnitude. Therefore, the effective use of interaction torques requires precise timing control of proximal limb deceleration (Herring and Chapman 1992; Hore et al. 2005b), which could have been difficult for the novices. One interpretation for the behavior of the novices is then the use of coupled shoulder–elbow extension throughout the downswing motion could have been a simplified method for them. Another interpretation may be that by not using the shoulder deceleration the novices can minimize the perturbing effect of interaction torques on the distal joint motions (Sainburg and Kalakanis 2000), and thereby they can assure the accuracy of movement speed at the finger even without accurately predicting the intersegmental dynamics of their arm when striking a piano key.

The effective use of shoulder flexion when the experts depress the keys

One interesting finding of the present study concerning the kinematics of the arm during key depression was the distinct expert-novice difference in the use of upper arm rotation. From the onset to the end of key depression, the experts used marked shoulder flexion. Because the shoulder flexion in the experts was proceeded by a greater burst of the AD and Biceps muscular activity, this shoulder joint motion appeared to be caused predominately by volitional active muscle contraction rather than by passive movement action. We also found that this shoulder flexion in the experts was coupled with a forward rotation of the finger at the MP and wrist joints as the fingertip depressed the key, thus indicating that the shoulder flexion was aimed to facilitate depression of the key by the finger. For the novices, on the other hand, small amount of shoulder extension predominated to generate a downward movement of the hand till the end of key depression. The novices mainly relied on shoulder and elbow extension for the downward movement of the forearm and hand. Interestingly, the characteristics of upper limb's joint kinematics for key-depression by the present novice players were quite similar to those observed during striking a computer key by ordinary people (Dennerlein et al. 2007). These findings suggest that the novices have used a fundamental keystroke synergy that is developed through everyday experience of key hitting and pressing tasks. The experts, on the other hand, have used a key-depression synergy that should be specifically acquired with a long-term training as a most efficient way to produce a target sound on the piano. These synergies could include the formation of attack angle as well as the posture of the limb at the end of key depression movement.

Expert-novice difference in attack angle formation

In line with our hypothesis, we found that the experts had a larger attack angle compared to the novices. The estimation of joint torques at the end of key depression for the present participants further indicated that at all loudness levels the experts had a significantly smaller MP joint torque than the novices. This was due to closer distance between the finger joint centers and key reaction force vector at the attack angle of the experts, which basically agrees with the findings from the previous reports (Harding et al. 1993; Jindrich et al. 2004). Our EMG data, on the other hand, provided evidenced that for both the experts and novices, loudness-dependent coactivation of the agonist and antagonist pairs of the upper limb muscles occurred starting from some short period before the finger-key contact and lasted till nearly the end of the key depression period. Stiffening of the joints in the whole upper limb in preparation for the upcoming large key reaction force at the key bottom moment therefore appears to be an essential mechanism for the piano key depression. The coactivation index value for the forearm of the experts was, on the other hand, less than that for the novices, suggesting that the level of stiffness at the wrist and finger joints could also be lower for the experts. This should be related to the fact that the experts understood that less joint stiffness was able to offset the upcoming wrist and finger joint torques at the key bottom moment with a larger attack angle. A reduction of the forearm muscular work thus can be expected with the use of the large attack angle in addition to reducing the mechanical stress at the finger joint.

Expert-novice difference in movement planning of the upper limb for key depression

The expert-novice difference in the coactivation index values at the distal muscles may implicate what variable is incorporated into the movement planning of the piano keystroke. Distal muscles with smaller physiological cross sectional area (PCSA) are commonly more sensitive to fatigue than the proximal ones. On the other hand, distal muscular activity predominates when playing the piano (Furuya et al. 2006a; Sforza et al. 2003), and its fatigue thus can lead to the loss of precise control of finger movement as well as the decrease in the key-depression force production capacity. The quality of the performance may then decline, and playing-related musculoskeletal disorders (PRMDs) may develop. The prevention of fatigue at the distal muscles can therefore be important in the movement planning of a keystroke on the piano. The results from optimization computations accounting for the PCSA of each muscle indicated that the CNS takes this variable into consideration in the planning of walking, running, and cycling movements (e.g., Herzog 2000; Prilutsky and Zatsiorsky 2002). In addition, behavioral studies suggest that the biomechanical property of human limbs is used in planning multi-joint movements (Dounskaia 2005; Goble et al. 2007; Graham et al. 2003). The planning of a piano keystroke in the experts thus seems to account for the PCSA of limb muscles and thereby preferably reduces the amount of coactivation at the distal finger muscles by using a vigorous rotation of the shoulder with massive musculatures. This may be acquired through years of training as a way to maximize the quality of performance and minimize the risk of PRMDs. In contrast, the novices' movement planning is likely to prioritize the simplification of intersegmental dynamics during the keystroke even at the expense of the physiological efficiency. A similar line of evidence has been reported for arm reach by the non-dominant hand, in which little shoulder motion produced small interaction torque at the elbow, and consequently greater elbow muscular effort was required than with the use of the dominant hand (Bagesteiro and Sainburg 2002; Sainburg and Kalakanis 2000).

Implications for the prevention of PRMDs

Piano performance involves a repetition of key-striking action reaching sometimes thousands of times per minute (Münte et al. 2002). Submaximal muscular efforts of compensating the perturbing joint torques from each keystroke may then create cumulative damage in muscles and tendons, especially in the hand and forearm over time (Dennerlein 2005). Indeed, researchers have reported that more than 60% of active piano players at some time experience PRMDs from acute pain to more serious symptoms such as tendonitis, carpal tunnel syndrome, and focal dystonia (Altenmuller 2003; Bragge et al. 2006; Furuya et al. 2006b). The PRMDs were most frequent at the finger/hand and forearm muscles (Furuya et al. 2006b). The present results which show the typical keystroke motion with the active use of shoulder flexion during key-depression to be associated with the smaller mechanical stress and muscular effort at these portions are thus considered to provide valuable information which can be used in the prevention of PRMDs, especially in novice players of the piano.

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Appendix

During the finger-key contacting period, torques ("key-force torque") from key reaction force are generated at the joints of the upper extremity. The key-force torque can be calculated as follows:

$$\tau = \mathbf{J}^{\mathrm{T}} \cdot \mathbf{F}$$

where τ is the key-force torque, $\mathbf{F}$ is the key-force ($\mathbf{F} = [Fx, Fy]$), and $\mathbf{J}$ is the Jacobian matrix described as follows:

$$\mathbf{J} = \begin{bmatrix} J_{11} & J_{12} & J_{13} & J_{14} \\ J_{21} & J_{22} & J_{23} & J_{24} \end{bmatrix}$$

$$J_{11} = -(A\sin\theta + B\sin(\theta+\phi) + C\sin(\theta+\phi+\psi) + D\sin(\theta+\phi+\psi+\varphi))$$

$$J_{12} = -(B\sin(\theta+\phi) + C\sin(\theta+\phi+\psi) + D\sin(\theta+\phi+\psi+\varphi))$$

$$J_{13} = -(C\sin(\theta+\phi+\psi) + D\sin(\theta+\phi+\psi+\varphi))$$

$$J_{14} = -D\sin(\theta+\phi+\psi+\varphi)$$

$$J_{21} = A\cos\theta + B\cos(\theta+\phi) + C\cos(\theta+\phi+\psi) + D\cos(\theta+\phi+\psi+\varphi)$$

$$J_{22} = B\cos(\theta+\phi) + C\cos(\theta+\phi+\psi) + D\cos(\theta+\phi+\psi+\varphi)$$

$$J_{23} = C\cos(\theta+\phi+\psi) + D\cos(\theta+\phi+\psi+\varphi)$$

$$J_{24} = D\cos(\theta+\phi+\psi+\varphi)$$

where constants are described as follows:

A length from shoulder to elbow
B length from elbow to wrist
C length from wrist to MP
D length from MP to fingertip
θ shoulder angle
ϕ elbow angle
ψ wrist angle
φ MP angle

These constants were computed using the measured position data of each joint center at the moment of the key's lowest position for each participant. For all participants, the key-force torque was then computed at all loudness levels while a given amount of key reaction force was assumed to be applied to the fingertip at the moments of the key's lowest position. For this purpose, the key reaction force at the moment of maximum key displacement was measured in a preliminary experiment using three expert and three novice piano players. A small uni-axial force transducer (Tec-gihan co., Kyoto, Japan) was fastened to the surface of the G3 key front using an adhesive strip, and it was struck by the thumb 10 times at the designated sound dynamics in the octave keystroke mode. The mean key reaction force at the *p*, *mp*, *mf*, and *f* levels were 2.3, 3.8, 6.5, 9.8 N, respectively, for the experts, and 2.3, 3.7, 6.4, and 10.1 N, respectively, for the novices. These values were doubled to approximate the sum of key reaction forces applied at the thumb and little finger, and inputted into the equation for each of the groups. The tangential force (Fx) was set to nil for simplicity of computation. The key-force torques at the MP, wrist, and elbow joints were computed. The shoulder joint torque was not computed because it was independent of the arm and hand postures.

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